SOLAR/2018-79/14



# Solar Energy System Performance Evaluation

REEDY CREEK UTILITY DISTRICT
OFFICE BUILDING
Lake Buena Vista, Florida
September, 1978 through February, 1979



U.S. Department of Energy

National Solar Heating and
Cooling Demonstration Program

National Solar Data Program

# NOTICE



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# SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

REEDY CREEK UTILITY DISTRICT
OFFICE BUILDING
LAKE BUENA VISTA, FLORIDA

SEPTEMBER 1978 THROUGH FEBRUARY 1979

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SECRETARY FOR
CONSERVATION AND SOLAR APPLICATIONS
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NATIONAL SOLAR DATA PROGRAM REPORTS

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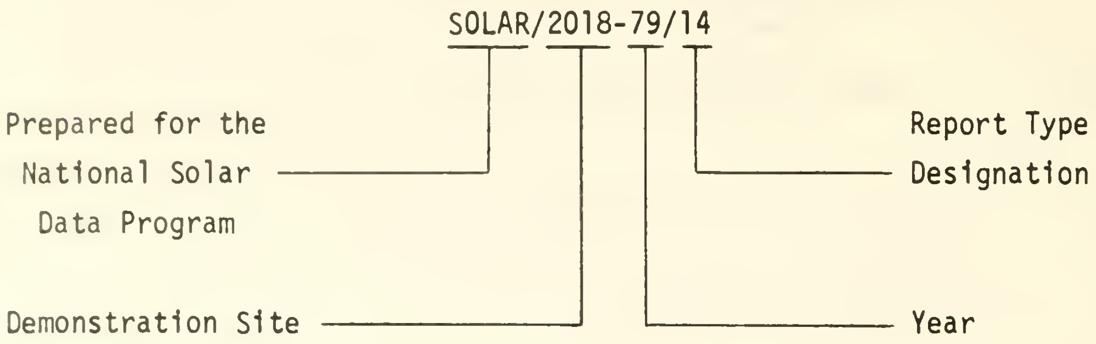


- Demonstration Site Number:

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  - Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

  - Solar Energy System Performance Evaluations are designated by the number 14.

  - Solar Project Descriptions are designated by the number 50.

  - Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy, Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

## 1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth in order to achieve a substantial reduction in non-renewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the System Performance Evaluation Report, is published on a regular basis. Each parameter

presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network.

All reports issued by the National Solar Data Program for the Reedy Creek solar energy system are listed in Section 6, References.

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Reedy Creek solar energy system. The analysis covers operation of the system from September 1978 through February 1979. The Reedy Creek solar energy system provides space heating, space cooling and domestic hot water to a two-story office building occupied by the Reedy Creek Utilities Company, Incorporated, Lake Buena Vista, Florida. A more detailed system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 2 presents a summary of the results and conclusions obtained while Section 5 presents a detailed assessment of the system thermal performance.

Acknowledgements are extended to those individuals involved in the operation of the Reedy Creek Utility District. Their insight and cooperation in the resolution of various on-site problems during the reporting period were invaluable.

## 2. SUMMARY AND CONCLUSIONS

This System Performance Evaluation Report provides an operational summary of the solar energy system installed at the Reedy Creek Utility District, an office building located in Lake Buena Vista, Florida. This analysis is conducted by evaluation of measured system performance and by comparison of measured weather data with long-term average climatic conditions. The performance of major subsystems is also presented.

The measurement data were collected [References 7-12]* by the National Solar Data Network (NSDN) [1] for the period September 1978 through February 1979. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report. This report includes: a brief system description, a review of actual performance during the report period, analysis of performance based on evaluation of climatic, load and operational conditions and an overall discussion of the results of analysis.

This performance evaluation report encompasses the space heating season at the Reedy Creek site. The previous seasonal report [14] covered the major cooling season, although some space cooling is generally required during eleven months of the year. Measured monthly values of ambient temperature during the six-month report period were slightly greater than normal with a measured average outdoor ambient temperature of 69°F versus the long-term average for the same period of 68°F. Measured heating degree-days have been less than the average (418 versus 626), while measured cooling degree-days have been slightly greater (1,142 versus 1,064). The average daily incident solar energy per unit area measured during the report period was 1,034 Btu/Ft$^2$. This was less than the long-term daily average of 1,177 Btu/Ft$^2$ for data taken 15 miles north in Orlando, Florida.

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*Numbers in brackets designate references listed in Section 6.

During the six-month report period, the solar energy system supplied all of the 0.89 million Btu demand for domestic hot water, all of the 25.84 million Btu demand for space heating and 35.39 million of the total 92.27 million Btu space cooling demand at the site.

The domestic hot water subsystem was by far the smallest load supported by the solar energy system. Usage in the office building is minimal, approximately 300 gallons per month, resulting from three hot water faucets located in lavatories. The domestic hot water demand is always completely supported by solar energy since there is no backup conventional or auxiliary system in the facility. During this six-month report period, the solar energy system supported all of the 0.89 million Btu demand for domestic hot water. This demand is down slightly from the 1.19 million Btu demand experienced during the previous six months.

The space heating load was the next largest load supported by the solar energy system. Space heating was required during all of the six-month period except September. The maximum load of 11.53 million Btu was experienced during January. There is no backup or auxiliary system for heating, so the solar energy system always supports the complete load. The solar energy system appears to have maintained a comfortable temperature within the building on all but one cold day in January when the average building temperature dropped to 60°F. The total space heating demand supported by the solar energy system for this six-month period was 25.84 million Btu, and this is significantly larger than the 1.25 million Btu demand occurring during the previous reporting period.

Space cooling was the largest load supported by the solar energy system. It is also the most difficult to support, requiring hotter water than the other systems, utilizing a conversion process rather than direct application, and experiencing losses to the environment from two storage tanks. A cooling demand was supported during each month in this reporting period, with a maximum of 38.03 million Btu in September and a minimum of 2.64 million Btu in February. The solar fraction for the space cooling system in those months was 0.32 and 0.94, respectively.

Space cooling demand for this six-month period was 92.27 million Btu as compared to 152.63 million Btu in the previous period. The average of the monthly solar fractions for space cooling during this period was 0.52, compared with 0.40 for the previous six months.

Electrical savings calculations provide a reasonable method of determining the overall impact that the solar energy system had on the energy consumption of a facility. The actual non-solar energy requirements for the Reedy Creek site are compared to those that would be required if the building used conventional heating, cooling and domestic hot water systems. For this six-month reporting period, the total electrical savings were 12.80 million Btu or 3,750 kilowatt hours. This is also an increase over the previous six-month period in which the electrical savings were 8.45 million Btu or 2,476 kilowatt hours.

During the period of this report there have been no significant equipment abnormalities or failures which would affect any of the performance parameters. A periodic evaluation and recalibration of the instrumentation sensors occurred in February. This operation is performed occasionally after a site has been on line for several months to determine the long-term stability or drifting of the instrumentation hardware. As a result, data was not gathered during five days in February. Since no significant system transients were taking place when this was done, the normal bridging processes were able to determine the monthly average values for February with no significant loss in accuracy. As is usual, the recalibration of sensors indicated some small changes in sensor characteristics during the year's use. Based on this information, new conversion constants were determined, and all of the data back through October 1978 was reanalyzed. As a result, many of the values shown in this report are slightly different from those which originally appeared in the monthly reports. These changes are generally small, do not significantly affect any of the conclusions and recommendations, and represent the most accurate data available.

The measured performance of the Reedy Creek solar energy system was somewhat less than the expected performance based on the performance evaluation summarized in Section 5 and the measured climatic conditions summarized above. However, it was better than the measured performance experienced during the previous six-month period. Less solar energy was used in this recent period (74.19 versus 143.32 million Btu), while, as mentioned earlier, the solar fraction for space cooling, the only solar fraction less than 100 percent, increased from 40 percent in the previous six-month period to the current 52 percent.

There are no apparent equipment malfunctions or severe climatic conditions preventing the space cooling system from meeting 80 percent of the demand as expected. It appears that the solar portion of the space cooling equipment (absorption chiller, hot and cold storage tanks) may not have sufficient capacity to support the actual load experience in the building.

The overall performance of the solar energy system at Reedy Creek during the reporting period has been good, and during the final month of February it has operated above its design level. This provided an overall solar fraction of 99 percent for that month.

## 3. SYSTEM DESCRIPTION

The Reedy Creek site is a two-story, 5,625 square foot concrete block office building located in Lake Buena Vista, Florida. The solar energy system is designed to provide all of the space heating and domestic hot water and 80 percent of the space cooling demand.

The collector subsystem is composed of a horizontal array of 16 parabolic trough collectors, manufactured by AAI Corporation, with tracking absorber tubes. The collector array is an integral part of the building's roof, with the collector subsystem oriented so that its major axis is in an east/west direction. The 16 absorber tubes are moved in unison in a north/south direction by the solar tracking system. The total collector aperture area is 3,840 square feet. Water is used as the heat collection, transfer, and storage medium. Collected solar energy is stored in a 10,000-gallon hot water tank, located adjacent to the building and shaded by the roof. Domestic hot water is provided by a heat exchanger immersed in this tank. Space heating is provided by circulation of hot water from the storage tank through heat exchangers located in the central air distribution system. No auxiliary energy is provided for either domestic hot water or space heating.

A 25-ton absorption chiller utilizes hot water from solar storage to provide chilled water to a 10,000-gallon cold water storage tank. For space cooling, water from this cold tank is circulated through heat exchangers located in the building's central air distribution system. Auxiliary cooling is provided by supplemental cold water from the utility district's central chiller plant, which is powered by fossil fuels.

The system, shown schematically in Figure 3-1, has five modes of solar operation.

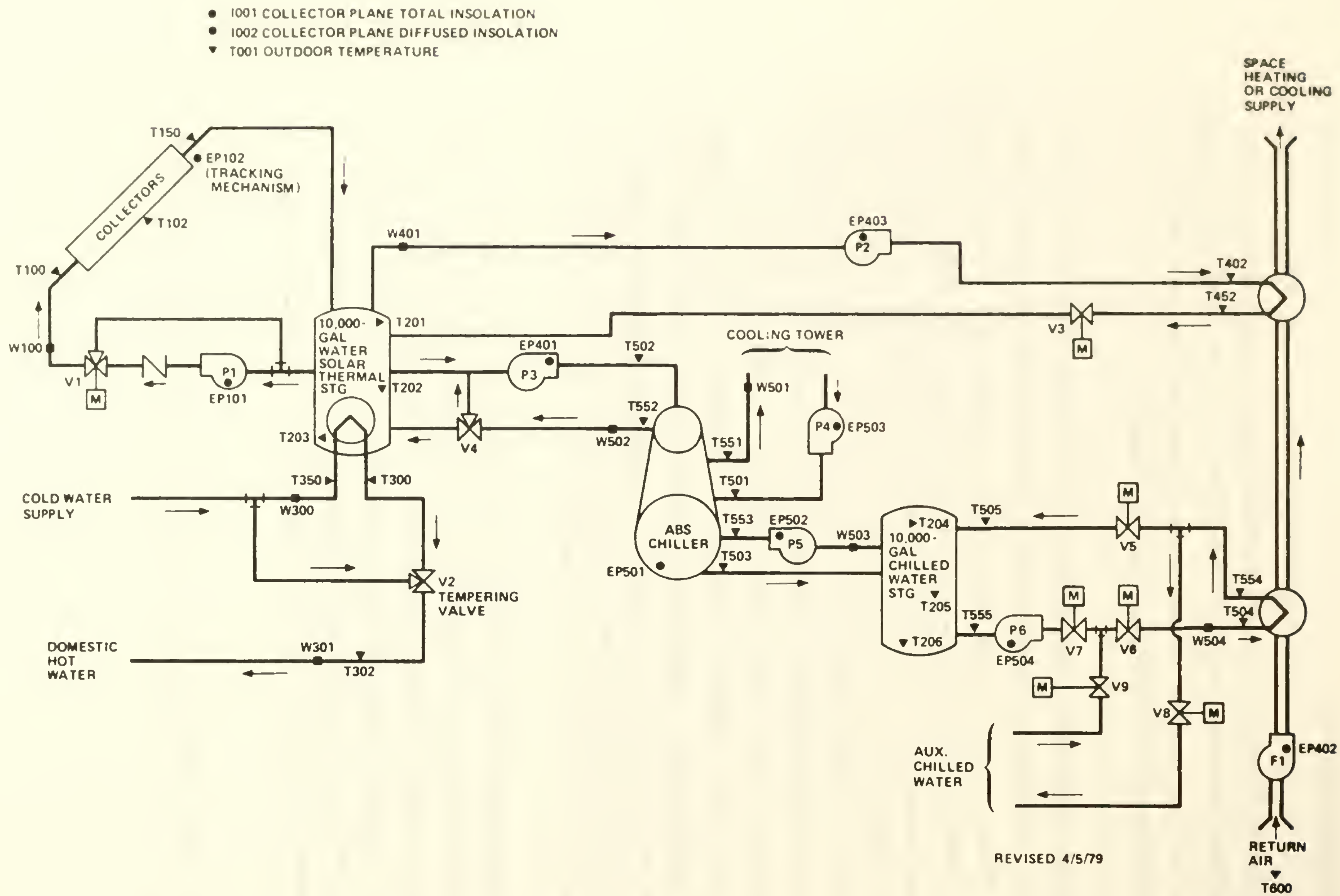


Figure 3-1 REEDY CREEK SOLAR ENERGY SYSTEM SCHEMATIC

Mode 1 - Collector-to-Storage: This mode is entered when the collector absorber plate temperature is 10°F higher than the temperature at the bottom of the hot storage tank (water thermal storage). Water is circulated through the collector array/storage loop until the temperature of the water at the bottom of storage rises to within 3°F of that of the collector absorber plate.

Mode 2 - Storage-to-Space Heating: This mode is entered when the temperature falls below the setting of the thermostats located in the occupied areas. Since this is the only means of space heating available, no minimum tank temperature is specified. Pump P2 causes hot water to flow directly from the storage tank to the heat exchanger in the air-handling unit, and back to the storage tank.

Mode 3 - Domestic Hot Water Heating: Domestic hot water is provided by passing city supply water through a heat exchanger immersed in the water thermal storage. No conventional water heater exists, thus water is heated only upon demand. A tempering valve is used when necessary to reduce the temperature of water leaving the heat exchanger. If the water is too hot, cold supply water is mixed with it in the tempering valve before going to the domestic hot water line.

Mode 4 - Chilled Water Production: This mode is entered when the temperature of the water in the top of the water thermal storage is at or above the generator operating temperature (nominally 180°F) and that of the water at the bottom of the 10,000-gallon chilled water storage is greater than 45°F. Hot water is drawn from water thermal storage to operate the generator section of the absorption chiller and cold water is circulated through the chiller from the chilled water storage. Energy is removed from the cold water, lowering its temperature. The energy is rejected through the cooling tower, and the cold water returns to the chilled water storage tank.

Mode 5 - Space Cooling: The space cooling mode is initiated when the building temperature exceeds the setting of the conditioned space thermostat. Chilled water from the chilled water storage is then circulated through heat exchangers in the building air distribution system. If the chilled water storage system is not able to meet the cooling load, an auxiliary conventional chilled water supply is available from the central energy plant.

## 4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Reedy Creek solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for the calculation of the daily and monthly performance of each component subsystem.

Each month a summary of overall performance of the Reedy Creek site and a detailed subsystem analysis are published. Monthly reports for the period covered by this System Performance Evaluation, September 1978 through February 1979, are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

## 5. PERFORMANCE ASSESSMENT

The performance of the Reedy Creek solar energy system has been evaluated for the September 1978 through February 1979 time period. Two perspectives have been taken in this assessment. The first looks at the overall system view in which the total solar energy collected, the system load and the measured values for solar energy used and system solar fraction are presented. Also presented, where applicable, are the expected values for solar energy used and system solar fraction. The expected values have been derived from a modified f-chart* analysis which uses measured weather and subsystem loads as inputs. The model used in the analysis is based on manufacturers' data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented. The second view presents a more in-depth look at the performance of individual components. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating subsystem. Included in this area are all parameters pertinent to the operation of each individual subsystem.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

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*f-chart is the designation of a procedure for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

## 5.1. Weather Conditions

Average values of the daily incident solar energy in the plane of the collector array and the average outdoor temperature measured at the Reedy Creek site during the report period are presented in Table 5.1-1.

Also presented in Table 5.1-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Likewise, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days are summed monthly.

The total solar energy incident on the collector array at the Reedy Creek site was less than the long-term average during all months of the reporting period. September 1978 had the greatest amount of radiation, and it was three percent below the long-term daily average for the month. December 1978 received the smallest amount of solar radiation; it was 20 percent less than the long-term daily average for December. The measured solar radiation for the six-month period was 12 percent below the long-term average.

The average measured outside ambient temperature for the reporting period was 69°F as compared with the long-term average of 68°F. The greatest deviation from the average occurred during November when the measured temperature was 5°F above the long-term average, and then in the following December when the measured temperature was 5°F below the long-term average.

TABLE 5.1-1

WEATHER CONDITIONS

| | Daily Incident Solar Energy Per Unit Area (0° Tilt)(Btu/Ft$^2$-Day) | | Ambient Temperature (°F) | | Heating Degree-Days | | Cooling Degree-Days | |
|---|---|---|---|---|---|---|---|---|
| Month | Measured | Long-Term Average | Measured | Long-Term Average | Measured | Long-Term Average | Measured | Long-Term Average |
| Sep 78 | 1,453 | 1,497 | 81 | 80 | 0 | 0 | 481 | 453 |
| Oct 78 | 1,113 | 1,305 | 74 | 74 | 0 | 0 | 293 | 288 |
| Nov 78 | 999 | 1,095 | 72 | 67 | 0 | 75 | 210 | 123 |
| Dec 78 | 740 | 925 | 67 | 62 | 61 | 140 | 110 | 62 |
| Jan 79 | 892 | 999 | 59 | 60 | 208 | 197 | 25 | 52 |
| Feb 79 | 1,004 | 1,243 | 59 | 62 | 149 | 184 | 23 | 86 |
| Total | ----- | ----- | -- | -- | 418 | 626 | 1,142 | 1,064 |
| Average | 1,034 | 1,177 | 69 | 68 | 70 | 104 | 190 | 177 |

## 5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the energy requirements, both solar and auxiliary thermal, for each subsystem. The portion of the total load provided by solar energy is defined to be the solar fraction of the load. This solar fraction is the measure of performance for the solar energy system when compared to design or expected solar contribution.

The thermal performance of the Reedy Creek solar energy system is presented in Table 5.2-1. For the six-month period, solar energy was used to satisfy 100 percent of both the hot water and space heating subsystem demands. During this time, on the average, 52 percent of the space cooling demand was supplied by solar energy, resulting in an average system solar fraction of 61 percent for the reporting period. Table 5.2-2 contains the coefficients of performance for the various subsystems as well as the overall system. The subsystem operating energies are based only on those components required by the presence of the solar equipment; if a piece of equipment would still be required in a non-solar facility, the operating energy associated with it is not included in these calculations. Increased usage of a subsystem generally causes an improvement in efficiency and COP. For this reason, the COP values for the space heating system increase during the winter months, and the COP values for the other systems increase during the warmer months when more sunlight is available. The N/A values appearing in the heating and cooling subsystem columns indicate that the subsystem was not used during that month.

This period included the majority of the heating season experienced at the Reedy Creek facility, and the minimum portion of the cooling season. Additionally, the solar energy incident during this period, 1,034 Btu/$ft^2$-day, is significantly less than that normally experienced during the previous six months of the year, 1,713 Btu/$ft^2$-day. These

TABLE 5.2-1

SYSTEM THERMAL PERFORMANCE

| Month | Solar Energy Collected (Million Btu) | System Load (Million Btu) | Solar Energy Used (Million Btu) | | Solar Fraction (Percent) | |
|---|---|---|---|---|---|---|
| | | | Expected | Measured | Expected | Measured |
| Sep 78 | 25.43 | 38.18 | * | 25.30 | * | 33 |
| Oct 78 | 16.25 | 23.80 | | 8.98 | | 39 |
| Nov 78 | 16.82 | 18.07 | | 9.67 | | 47 |
| Dec 78 | 10.86 | 12.98 | | 6.33 | | 54 |
| Jan 79 | 16.41 | 15.44 | | 11.66 | | 93 |
| Feb 79 | 18.71 | 11.31 | | 12.25 | | 98 |
| Total | 104.48 | 119.78 | | 74.19 | | |
| Average | 17.41 | 19.96 | | 12.37 | | 61 |

*The collectors at this site are of a type that cannot be analyzed by the f-chart procedure. Therefore, expected values of solar energy used and solar fraction are not available.

TABLE 5.2-2

SOLAR ENERGY SYSTEM COEFFICIENTS OF PERFORMANCE

| Month | Solar Energy System COP | Collector Array Subsystem COP | Space Heating Subsystem Solar COP | Space Cooling Subsystem Solar COP |
|---|---|---|---|---|
| Sep 78 | 5.46 | 17.18 | N/A | 7.98 |
| Oct 78 | 4.06 | 14.51 | 49.00 | 7.76 |
| Nov 78 | 4.11 | 13.46 | 93.00 | 7.83 |
| Dec 78 | 4.62 | 11.67 | 108.75 | 4.52 |
| Jan 79 | 3.65 | 13.68 | 103.87 | N/A |
| Feb 79 | 7.52 | 17.32 | 42.70 | 10.32 |
| Total Period | 4.82 | 14.80 | 69.65 | 7.37 |

statistics combine to form a situation in which it is difficult for the solar energy system to support the cooling load. For instance in December, while the hot storage tank was supporting the heating load, there were only six occasions when the solar energy system could raise the hot tank temperature sufficiently to support the absorption chiller. The absorption chiller was then only operated for short periods of time, since it reduced the hot storage tank temperature more rapidly than the solar energy system could replenish it, due to the low insolation measured in December. The result is that even though the absorption chillers operated six times during December, the average temperature of the chilled water storage tank was a relatively high 67°F, dropping to a low of only 59°F. This necessitated the use of the auxiliary chilled water subsystem to support the cooling load. January produced a larger amount of insolation, but also a larger heating load to be supported by the hot storage tank. Consequently, the hot tank never got hot enough to allow operation of the absorption chillers. The small cooling load soon exhausted the remaining capacity of the cold storage tank, and the auxiliary chilled water subsystem was used to support the cooling load. As was expected, the solar energy system was capable of supporting a greater cooling load during the other months of the reporting period.

## 5.3 Subsystem Performance

The Reedy Creek solar energy installation may be divided into five subsystems:

1) Collector array
2) Storage
3) Hot water
4) Space heating
5) Space cooling.

Each subsystem is evaluated by the techniques defined in Section 4 and is numerically analyzed each month for the monthly performance reports. This section presents the results of integrating the monthly data available on the three subsystems for the period September 1978 through February 1979.

### 5.3.1 Collector Array Subsystem

Collector array performance is described by comparison of the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i \tag{1}$$

where: $\eta_c$ = Collector Array Efficiency (CAREF)

$Q_s$ = Collected Solar Energy (SECA)

$Q_i$ = Incident Solar Energy (SEA).

The gross collector array area is 1,932 square feet. The measured monthly values of incident solar energy, collected solar energy, and collector array efficiency are presented in Table 5.3.1-1.

Evaluation of collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yields operational collector efficiency. Operational collector efficiency, $\eta_{co}$, is computed as follows:

$$\eta_{co} = Q_s / \left( Q_{oi} \times \frac{A_p}{A_a} \right) \tag{2}$$

where: $Q_s$ = Collected Solar Energy (SECA)

$Q_{oi}$ = Operational Incident Energy (SEOP)

$Q_p$ = Gross Collector Area (product of the number of collectors and the total envelope area of one unit) (GCA)

$A_a$ = Gross Collector Array Area (total area perpendicular to the solar flux vector including all mounting, connecting and transport hardware (GCAA).

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

TABLE 5.3.1-1

COLLECTOR ARRAY PERFORMANCE

| Month | Incident Solar Energy (Million Btu) | Collected Solar Energy (Million Btu) | Collector Array Efficiency | Operational Incident Energy (Million Btu) | Operational Collector Efficiency |
|---|---|---|---|---|---|
| Sep 78 | 167.37 | 25.43 | 0.15 | 120.47 | 0.21 |
| Oct 78 | 132.48 | 16.25 | 0.12 | 85.26 | 0.19 |
| Nov 78 | 115.08 | 16.82 | 0.15 | 82.14 | 0.20 |
| Dec 78 | 88.04 | 10.86 | 0.12 | 56.05 | 0.19 |
| Jan 79 | 106.22 | 16.41 | 0.15 | 76.55 | 0.21 |
| Feb 79 | 107.99 | 18.71 | 0.17 | 76.53 | 0.24 |
| Total | 717.18 | 104.48 | ---- | 497.00 | ---- |
| Average | 119.53 | 17.41 | 0.14 | 82.83 | 0.21 |

This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are also presented in Table 5.3.1-1.

Collector array efficiency may be viewed from two perspectives. The first assumes that the efficiency be based upon all available solar energy; however, that point of view makes the operation of the control system a part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum, thus the energy is not collected. The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5.3.1-1.

The second viewpoint assumes the efficiency be based upon only the incident energy during periods of collection. The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency." Efficiency computed by this method is used in the following discussion.

The average operational collector efficiency of the collector array during the six-month reporting period was 21 percent. The variation in collector array efficiency was quite small during the six-month period. This is apparently due to modifications made to the tracking system in August which improved its reliability. In addition, there was only a 13°F difference between the maximum and minimum of the monthly average of the thermal storage tank temperature. This resulted in less variation in the collector inlet temperature which, in turn, reduced the variation in the collector array efficiency.

The results of the collector array performance at Reedy Creek have been presented during the previous reporting period in Reference [13]. For the nominal system collector array operating point of 0.28, the average operational collector efficiency of 0.21 is very nearly that predicted by the manufacturer's data. This value is slightly less than experienced during the previous six-month period which might be expected due to the lower angle of the sun during the winter months.

### 5.3.2 Storage Subsystem

Storage subsystem performance is described by comparison of energy to storage, energy from storage and change in stored energy. The ratio of the sum of energy from storage and change in stored energy to energy to storage is defined as storage efficiency, $\eta_s$. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si} \tag{3}$$

where:

$\Delta Q$ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value) (STECH).

$Q_{so}$ = energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium (STEO).

$Q_{si}$ = energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium (STEI).

Evaluation of the system storage performance under actual transient system operation and weather conditions can be performed using the parameters listed above. The utility of these measured data in evaluation of the overall storage design can be illustrated in the derivation presented below.

The overall thermal properties of the storage subsystem design can be derived empirically as a function of storage average temperature (average storage temperature for the reporting period) and the ambient temperature in the vicinity of the storage tank.

An effective storage heat transfer coefficient (C) for the storage subsystem can be defined as follows:

$$C = (Q_{si} - Q_{so} - \Delta Q_s)/[(\bar{T}_s - \bar{T}_a) \times t] \ \frac{\text{Btu}}{\text{Hr-°F}} \qquad (4)$$

where:

$C$ = effective storage heat transfer coefficient

$Q_{si}$ = energy to storage (STEI)

$Q_{so}$ = energy from storage (STEO)

$\Delta Q_s$ = change in stored energy (STECH)

$\bar{T}_s$ = storage average temperature (TS)

$\bar{T}_a$ = average ambient temperature in the vicinity of storage (TE)

$t$ = number of hours in the month (HM).

The effective storage heat transfer coefficient is comparable to the heat loss rate defined in ASHRAE Standard 94-77 [6]. It has been calculated for each month in this report period and included, along with Storage Average Temperature, in Table 5.3.2-1.

During the month of September, the collection and usage of solar energy was significantly greater than during any of the other months of this reporting period. Consequently, there were significant temperature fluctuations occurring on an hourly and daily basis that are not indicated in the average storage temperature value for the month. Because of this, calculation of the heat loss coefficient would not be representative for the month of September, and it is therefore not included in Table 5.3.2-1. The calculations performed for the remaining five months show significant

TABLE 5.3.2-1

STORAGE SUBSYSTEM PERFORMANCE

| Month | Energy To Storage (Million Btu) | Energy From Storage (Million Btu) | Change In Stored Energy (Million Btu) | Storage Efficiency | Storage Average Temperature (°F) | Effective Storage Heat Loss Coefficient (Btu/Hr°-F) |
|---|---|---|---|---|---|---|
| Sep 78 | N/A | N/A | N/A | N/A | N/A | N/A |
| Oct 78 | 16.25 | 8.98 | -0.24 | 0.54 | 168 | 107 |
| Nov 78 | 16.82 | 9.67 | 0.73 | 0.61 | 167 | 94 |
| Dec 78 | 10.86 | 6.33 | -1.63 | 0.43 | 162 | 87 |
| Jan 79 | 16.41 | 11.66 | 0.91 | 0.77 | 155 | 54 |
| Feb 79 | 18.71 | 12.25 | -1.32 | 0.58 | 166 | 108 |
| Total | 79.05 | 48.89 | -1.55 | ---- | --- | --- |
| Average | 15.81 | 9.78 | -0.31 | 0.59 | 164 | 90 |

variance in the values for the heat loss coefficient, with an average value of 90 Btu/Hr-°F. The thermal storage tank has a surface area of approximately 650 square feet, and this results in an R value for the tank insulation of 7.2.

As the flow of energy into and out of the storage tank is large, the temperature difference between the tank and the ambient environment can fluctuate significantly. This causes the rate of energy loss to the environment to change as energy is added or removed from the tank by the solar and air-handling equipment. The result is that the calculation of the heat loss coefficient may not be accurate when determined while the storage tank temperature is changing significantly.

In an attempt to avoid this problem, additional calculations were performed for the hot and cold storage tanks using periods of time when there was no energy added or removed from the tanks by the subsystems. Typically this occurred over weekends or holidays when the building was not occupied.

Table 5.3.2-2 summarizes the occurrence of those conditions for the two tanks during the reporting period. The average value for the Effective Heat Transfer Coefficient for the hot storage tank is 147 Btu/Hr°F, while for the cold storage tank it is 112 Btu/Hr°F. Since both tanks have identical surface areas of 650 square feet, this represents R-values of 4.4 and 5.8, respectively.

Thermal stratification within the two storage tanks results in uncertainty in determining the energy content within the tanks. Both storage tanks are equipped with three temperature sensors, located approximately at the top, middle and bottom of the liquid contained within the tank. The average of the three readings from these sensors is used to calculate the thermal energy contained within the tanks, and

TABLE 5.3.2-2

TRANSIENT PERFORMANCE OF THERMAL STORAGE TANKS

| HOT TANK | | | | | COLD TANK | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date | Average Tank Temp.(°F) | Average Ambient Temp.(°F) | Avg. Change In Stored Energy (Million Btu) | C (Btu/Hr-°F) | Date | Average Tank Temp.(°F) | Average Ambient Temp.(°F) | Avg. Change In Stored Energy (Million Btu) | C (Btu/Hr-°F) |
| Oct 14 | 166 | 75 | -0.366 | -168 | Sep 2-4 | 54 | 80 | 0.067 | 107 |
| Jan 20 | 162 | 69 | -0.272 | -122 | Sep 10 | 62 | 80 | 0.025 | 58 |
| Jan 27 | 147 | 63 | -0.274 | -136 | Sep 23 | 57 | 79 | 0.059 | 112 |
| Feb 17 | 160 | 62 | -0.377 | -160 | Sep 30-Oct 1 | 71 | 79 | 0.020 | 104 |
| | | | | | Oct 28 | 63 | 75 | 0.034 | 118 |
| | | | | | Nov 11, 12 | 71 | 70 | 0.003 | 126 |
| | | | | | Nov 25 | 65 | 69 | 0.015 | 156 |
| | | | | | Dec 2, 3 | 70 | 74 | 0.016 | 166 |
| | | | | | Dec 23, 25 | 70 | 67 | -0.015 | 183 |
| | | | | | Dec 27-31 | 70 | 65 | 0.012 | 100 |
| | | | | | Jan 3 | 68 | 37 | -0.101 | 135 |
| | | | | | Jan 6 | 68 | 66 | 0.007 | 145 |
| | | | | | Jan 14 | 70 | 63 | -0.011 | 66 |
| | | | | | Jan 27, 29 | 70 | 55 | -0.040 | 111 |
| | | | | | Feb 1 | 69 | 44 | -0.045 | 75 |
| | | | | | Feb 3, 5 | 68 | 56 | -0.025 | 68 |
| | | | | | Feb 9, 11 | 70 | 51 | -0.036 | 79 |
| Average | 158.75 | 67.5 | | -147 | | | | | 112 |

consequently, the energy lost from the tanks. Thermal stratification, which occurs when there is no circulation, alters the energy distribution and possibly can introduce error into the determination of the energy content of the tanks. Figure 5.3.2-1 shows the effect of stratification by indicating the temperatures at the three sensors in the thermal storage tank over a three-day period. During those days the only circulation in the tank occurred as the result of collector operation on the first and third day. During the period of approximately 40 hours, after the collectors stopped operating on the first day, until they operated again on the third day, the temperature change is due to conduction to the atmosphere and stratification.

Notice that the top two sensors indicate very similar temperatures and these temperatures change more slowly than the temperature indicated by the bottom sensor. Therefore, an energy leakage calculation based on an average temperature may slightly overestimate the leakage rate from the top and middle sections, and underestimate that from the bottom. However, these two effects compensate for each other, increasing the confidence in the overall leakage calculation. Because of this, it is believed that the stratification probably has a relatively small effect on accuracy of the leakage calculation, and the actual magnitude cannot be known precisely without a detailed temperature profile of the tanks.

When using this second, short-term calculation method, the empirical determination of the heat loss coefficient still shows substantial variation between the insulation values of the two tanks. More scatter is observed in the data involving the cold tank. This is expected due to the smaller difference in temperature of the fluid within the cold tank and the ambient temperature.

No design values exist for the insulation on these tanks. If it may be assumed that the desire was to insulate the two tanks to the same R-value, then a nominal value of R-5, the average of the two values obtained above, may be used as the nominal insulation goal. This variation in the insulation values emphasizes the utility of establishing system characteristics based on measured data.

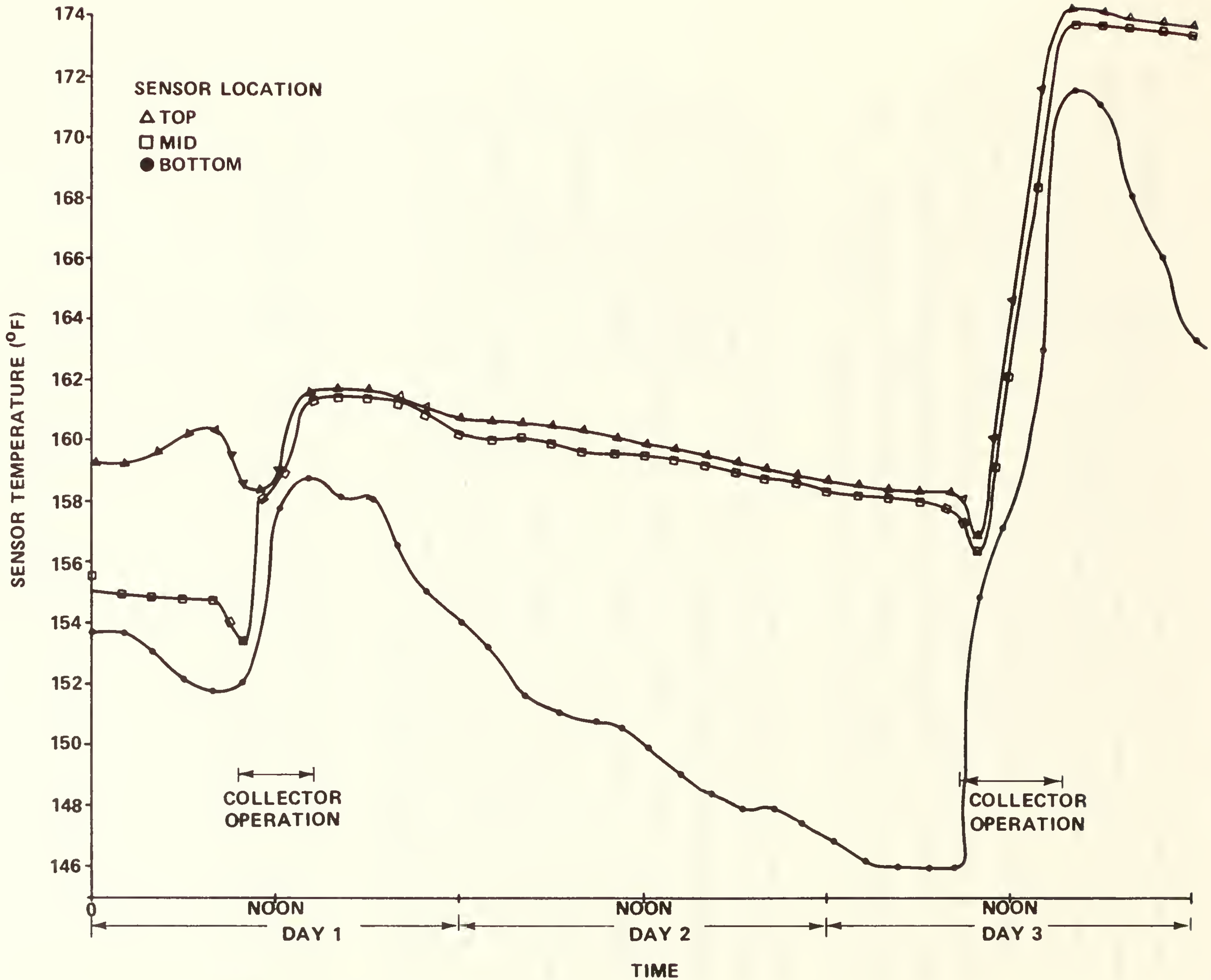


Figure 5.3.2-1 THERMAL STORAGE STRATIFICATION

### 5.3.3 Hot Water Subsystem

The performance of the hot water subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total hot water load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the hot water solar fraction. The calculated hot water solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total hot water load supported by solar energy. The performance of the hot water subsystem is presented in Table 5.3.3-1.

The hot water subsystem at Reedy Creek consists of a heat exchanger immersed in the hot water solar storage tank. Incoming potable water is heated during its passage through this tank. A tempering valve with a control set point of 140°F controls the maximum temperature of water delivered to the user. No storage of hot water is provided, and there is no provision for the addition of auxiliary energy. Water is heated upon demand and then only to the temperature of the tank. No estimates of the hot water consumption were made in the initial projections of loads, for it was known that this application of hot water heating would provide minimal usage. There are only three hot water faucets in the building, and all are supplied by the solar energy system.

Analysis of the monthly subsystem performance shows that approximately 300 gallons of hot water are consumed each month. The temperature of this water is increased by a nominal 70°F.

TABLE 5.3.3-1

HOT WATER SUBSYSTEM PERFORMANCE

| Month | Hot Water Heating Load (Million Btu) | Energy Consumed (Million Btu) | | | Measured Solar Fraction (Percent) |
|---|---|---|---|---|---|
| | | Solar | Auxiliary Thermal | Auxiliary | |
| Sep 78 | 0.15 | 0.15 | 0 | 0 | 100 |
| Oct 78 | 0.11 | 0.11 | 0 | 0 | 100 |
| Nov 78 | 0.21 | 0.21 | 0 | 0 | 100 |
| Dec 78 | 0.15 | 0.15 | 0 | 0 | 100 |
| Jan 79 | 0.14 | 0.14 | 0 | 0 | 100 |
| Feb 79 | 0.13 | 0.13 | 0 | | 100 |
| Total | 0.89 | 0.89 | - | 0 | - |
| Average | 0.15 | 0.15 | 0 | 0 | 100 |

### 5.3.4 Space Heating Subsystem

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction. The calculated heating solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space heating load supported by solar energy. The measured monthly values of these performance factors are presented in Table 5.3.4-1.

The space heating subsystem at Reedy Creek consists of a heat exchanger, located in the air distribution system of the building, which is supplied with hot water from solar storage. There is no auxiliary system of any type for space heating.

During the reporting period, a total of 25.84 million Btu of energy were supplied to the building. This is 95 percent of the heating load experienced during the past 12 months. Solar energy has supplied 100 percent of this demand, and appears to have maintained a comfortable temperature within the building.

TABLE 5.3.4-1

HEATING SUBSYSTEM PERFORMANCE

| Month | Space Heating Load (Million Btu) | Energy Consumed (Million Btu) | | | Measured Solar Fraction (Percent) |
|---|---|---|---|---|---|
| | | Solar | Auxiliary Thermal | Auxiliary | |
| Sep 78 | 0 | 0 | 0 | 0 | 100 |
| Oct 78 | 0.49 | 0.49 | 0 | 0 | 100 |
| Nov 78 | 0.93 | 0.93 | 0 | 0 | 100 |
| Dec 78 | 4.35 | 4.35 | 0 | 0 | 100 |
| Jan 79 | 11.53 | 11.53 | 0 | 0 | 100 |
| Feb 79 | 8.54 | 8.54 | 0 | 0 | 100 |
| Total | 25.84 | 25.84 | 0 | 0 | --- |
| Average | 4.31 | 4.31 | 0 | 0 | 100 |

### 5.3.5 Space Cooling Subsystem

The performance of the space cooling subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space cooling load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the cooling solar fraction. The calculated cooling solar fraction is the indicator of performance for the subsystem because it defines the percentage of the total space cooling load supported by solar energy. The measured monthly values of these performance factors are presented in Table 5.3.5-1.

The solar space cooling system at Reedy Creek consists of an Arkla 25-ton absorption cycle chiller (Model WFB-300) and a 10,000-gallon cold water storage tank. Cold water is produced by the chiller and stored in the tank. This water is then circulated through heat exchangers located in the air distribution system of the building to provide space cooling. The air distribution system has two zones corresponding to the two floors of the building. Maintenance of the building interior temperature is controlled by thermostats located in these two zones. When the supply of solar chilled water is insufficient to satisfy the demand for cooling, the system automatically shifts to chilled water produced by the central energy plant. After the auxiliary system has supplied the load for one-half hour, the system checks to see if sufficient cooling capacity exists within the solar chilled water storage tank. If so, then operation with solar is resumed; if not, the auxiliary cooling is continued. The production of this auxiliary chilled water is completely separate from the solar energy system and is produced by burning conventional fuels.

Solar energy is supplied to the generator of the absorption cycle water chiller to produce chilled water. A conventional cooling tower

TABLE 5.3.5-1

COOLING SUBSYSTEM PERFORMANCE

| Month | Total Cooling Load (Million Btu) | Auxiliary Portion of Load (Million Btu) | Solar Portion of Load (Million Btu) | Solar Energy Consumed (Million Btu) | Chiller COP | Solar Fraction (Percent) |
|---|---|---|---|---|---|---|
| Sep 78 | 38.03 | 25.68 | 12.35 | 25.15 | 0.40 | 32 |
| Oct 78 | 23.21 | 14.59 | 8.62 | 8.38 | 0.60 | 37 |
| Nov 78 | 16.93 | 9.53 | 7.40 | 8.53 | 0.59 | 44 |
| Dec 78 | 8.49 | 5.94 | 2.55 | 1.84 | 0.59 | 30 |
| Jan 79 | 2.97 | 0.97 | 2.00 | 0 | ---- | 67 |
| Feb 79 | 2.64 | 0.17 | 2.47 | 3.57 | 0.57 | 94 |
| Total | 92.27 | 56.88 | 35.39 | 47.49 | ---- | -- |
| Average | 15.38 | 9.48 | 5.90 | 9.50 | 0.55 | 51 |

dissipates this energy plus the energy removed from the chilled water storage tank. The primary function of the solar energy system at Reedy Creek is the production and storage of chilled water to be used for space cooling. The absorption cycle water chiller is critical to the performance of the space cooling subsystem.

Table 5.3.5-1 summarizes the cooling subsystem performance for the reporting period. The total measured space cooling demand was 92.27 million Btu, of which solar energy provided 51 percent. The nominal chiller coefficient of performance was 0.55.

A space cooling demand existed during every month of this reporting period, and solar energy supported a portion of that load during each month. Auxiliary energy was also required for support of the space cooling load during every month. During the month of January, there was a relatively small cooling load, and the cold storage tank was cold enough to support 67 percent of the load. However, the thermal storage tank never became hot enough to support operation of the absorption chiller. Therefore, the results presented in Table 5.3.5-1 correctly indicate a cooling solar fraction of 67 percent, but show no solar energy consumed.

During the last five months of this six-month period, the absorption chiller operated very well with the COP ranging from a high of 0.60 to a low of 0.57. This is most likely a result of the experimentation done during the previous months to determine the effect of generator operating temperatures. Apparently a near optimum operating routine has been found, and has resulted in excellent absorption chiller performance.

## 5.4 Operating Energy

Operating energy for the Reedy Creek facility solar energy system is defined as the energy required to transport solar energy to the point of use. Total operating energy for this system consists of energy collection and storage subsystem operating energy and space heating subsystem operating energy. Operating energy is electrical energy that is used to support the subsystems without affecting their thermal state. Measured monthly values for subsystem operating energy are presented in Table 5.4-1.

The average monthly ECSS operating energy for the months September 1978 through February 1979 was 1.18 million Btu. This operating energy represents the electrical power required by the collector pumps to collect a monthly average of 17 million Btu of solar energy. This collected energy is nearly 15 times the amount of energy used to operate the collector and storage subsystems.

The major contributor to both the heating and cooling operating energies is the air-handler unit which is located in the central air distribution system of the building. This unit provides all the air circulation. The operation of this air handler would be required for any type of heating or cooling system. The reported operating energies then represent a total subsystem demand and not a solar portion only.

Space heating was required during five of the six months of the reporting period. The total operating energy consumed was 3.31 million Btu, which represents only 11 percent of the total system operating energy.

The space cooling subsystem consumed a total of 19.59 million Btu of operating energy, an average of 3.26 million Btu per month. This sum includes generator and evaporator supply pump power in addition to internal power for the absorption cycle chiller, cold water recirculation pump power and the applicable portion of the air handler power. The operating energy for the space cooling subsystem accounts for more than 63 percent of the total system operating energy.

TABLE 5.4-1

SYSTEM OPERATING ENERGY

| Month | ECSS Operating Energy (Million Btu) | Space Cooling Operating Energy (Million Btu) | Space Heating Operating Energy (Million Btu) | Total Operating Energy (Million Btu) |
|---|---|---|---|---|
| Sep 78 | 1.48 | 6.21 | 0 | 7.69 |
| Oct 78 | 1.12 | 4.08 | 0.10 | 5.30 |
| Nov 78 | 1.25 | 3.96 | 0.14 | 5.35 |
| Dec 78 | 0.93 | 2.00 | 0.57 | 3.50 |
| Jan 79 | 1.20 | 1.89 | 1.50 | 4.59 |
| Feb 79 | 1.08 | 1.45 | 1.00 | 3.53 |
| Total | 7.06 | 19.59 | 3.31 | 29.96 |
| Average | 1.18 | 3.26 | 0.55 | 4.99 |

## 5.5 Energy Savings

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution, and the resulting energy savings are adjusted to reflect the coefficient of performance (COP) of the auxiliary source being supplanted by solar energy. For savings calculations, the baseline system is usually taken as the auxiliary system that exists at the site with savings being realized whenever solar energy can be employed to supplement its use. Since no auxiliary system exists at Reedy Creek for either the space heating or the hot water subsystems, a direct conversion heat pump system with a nominal COP of 2.5 for space heating and a nominal COP of 2 for space cooling has been assumed. The actual COP value is calculated from a quadratic curve fit as a function of ambient temperature.

The estimated difference between the electrical requirements of the conventional system carrying the full load and the actual electrical energy consumed by the system are defined as the savings presented in Table 5.5-1. The three types of savings: 1) heating electrical savings; 2) cooling electrical savings; and 3) hot water electrical savings, are included in Table 5.5-1. The energy collection and storage subsystem operating energy is not included in the subsystem electrical energy savings and must be algebraically added to obtain the total electrical savings.

Comparison of the hot water electrical savings with the hot water load in Table 5.3.3-1 shows that the savings is identical to this load. There was no operating energy required to operate the hot water subsystem.

TABLE 5.5-1

ENERGY SAVINGS

| Month | Electrical Energy Savings (Million Btu) | | | Solar Operating Energy (Million Btu) | Net Savings Electrical | |
|---|---|---|---|---|---|---|
| | Hot Water | Space Heating | Space Cooling | | Million Btu | kwh |
| Sep 78 | 0.15 | 0 | 3.02 | 1.48 | 1.69 | 495 |
| Oct 78 | 0.11 | 0.18 | 2.37 | 1.12 | 1.54 | 451 |
| Nov 78 | 0.21 | 0.35 | 1.87 | 1.25 | 1.18 | 346 |
| Dec 78 | 0.15 | 1.68 | 0.61 | 0.93 | 1.51 | 442 |
| Jan 79 | 0.14 | 4.63 | 0.39 | 1.20 | 3.46 | 1,160 |
| Feb 79 | 0.13 | 3.40 | 0.47 | 1.08 | 2.92 | 856 |
| Total | 0.89 | 10.24 | 8.73 | 7.06 | 12.80 | 3,750 |
| Average | 0.15 | 1.71 | 1.46 | 1.18 | 2.13 | 625 |

Heating savings for the period were 10.24 million Btu. The significant portion of these savings occurred only during the last three months of the report period, thus the average monthly figure for the season may not be meaningful. Since no auxiliary source of energy to supply the space heating load exists at Reedy Creek, these savings are identical to the load supplied divided by the temperature dependent COP value of the heat pump less the operating energy needed to transport the energy from storage to the conditioned space.

Positive savings were realized from the space heating subsystem where 25.84 million Btu were delivered to satisfy 100 percent of the space heating load at a cost of 3.31 million Btu of operating energy. The total savings were 10.24 million Btu, which indicates an average heat pump heating COP of 1.91 during the six-month period.

Cooling savings have averaged 1.46 million Btu/month throughout the report period or 428 kwh/month. The savings as reported are heavily influenced by the inclusion of the air circulation fans in the building which would be used in any case to provide internal air circulation. The reported operating energy for the cooling subsystem could be reduced by a factor of 10 if this energy were not charged against the operation of the solar energy system.

Solar energy supplied 51 percent of the space cooling load in an average month during the report period, and a total savings of 8.73 million Btu were realized.

## 6. REFERENCES


1. U.S. Department of Energy, National Solar Data Network, Prepared under Contract Number EG-77-C-01-4049, by IBM Corporation, December, 1977.

2. J. T. Smok, V. S. Sohoni, J. M. Nash, "Processing of Instrumented Data for the National Solar Heating and Cooling Demonstration Program," Conference on Performance Monitoring Techniques for Evaluation of Solar Heating and Cooling Systems, Washington, D.C., April, 1978.

3. E. Streed, et. al., Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program, NBSIR 76-1137, National Bureau of Standards, Washington, August, 1976.

4. Mears, J. C. Reference Monthly Environmental Data for Systems in the National Solar Data Network. Department of Energy report SOLAR/0019-79/36, Washington, D.C., 1979.

5. ASHRAE Standard 93-77, Methods of Testing to Determine the Thermal Performance of Solar Collectors, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

6. ASHRAE Standard 94-77, Methods of Testing Thermal Storage Devices Based on Thermal Performance, The American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc., New York, NY, 1977.

* 7. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-78/09, Department of Energy, Washington (September, 1978).

* 8. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-78/10, Department of Energy, Washington (October, 1978).

* 9. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-78/11, Department of Energy, Washington (November, 1978).

* 10. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-78/12, Department of Energy, Washington (December, 1978).

* 11. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-79/01, Department of Energy, Washington (January, 1979).

* 12. Monthly Performance Report, Reedy Creek Utilities, SOLAR/2018-79/02, Department of Energy, Washington (February, 1979).

13. W. H. McCumber, Jr., "Comparison of Actual Collector Array Performance With Predicted Performance", Solar Heating and Cooling Systems Operational results Conference, Colorado Springs, Colorado (November 28 - December 1, 1978).

* 14. Solar Energy System Performance Evaluation, Reedy Creek Utility District Office Building, SOLAR/2018-78/14, Department of Energy, Washington (March-August 1978).

* Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

## APPENDIX A

## DEFINITION OF PERFORMANCE FACTORS AND SOLAR TERMS

### COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

## STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

## ENERGY COLLECTION AND STORAGE SUBSYSTEM

The energy collection and storage subsystem (ICSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total solar energy incident on the gross collector array area. This is the area of the collector array energy-removing aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (SCOPE) is the critical operating energy required to support the ECSS heat transfer loops.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem. In addition, the solar energy supplied to the subsystem, along with solar fraction, is tabulated.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- FOSSIL ENERGY SAVINGS (HWSVF) is the estimated difference between the fossil energy requirements of the alternative conventional system (carrying the full load) and the actual fossil energy requirements of the subsystem.

- SUPPLY WATER TEMPERATURE (TSW) is the average inlet temperature of the water supplied to the subsystem.

- AVERAGE HOT WATER TEMPERATURE (THW) is the average temperature of the outlet water as it is supplied from the subsystem to the load.

- HOT WATER USED (HWCSM) is the volume of water used.

## SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

- AMBIENT TEMPERATURE (TA) is the average ambient dry bulb temperature at the site.

## SPACE COOLING SUBSYSTEM

The space cooling subsystem is characterized by performance factors accounting for the complete energy flow to and from the subsystem. The average building temperature and the average ambient temperature are tabulated to indicate the relative performance of the subsystem in satisfying the space cooling load and in controlling the temperature of the conditioned space.

- SPACE COOLING LOAD (CL) is the total energy, including sensible and latent, removed from the air in the space-cooling area of the building.

- SOLAR FRACTION OF LOAD (CSFR) is the percentage of the demand which is supported by solar energy.

- SOLAR ENERGY USED (CSE) is the amount of solar energy supplied to the space-cooling subsystem.

- OPERATING ENERGY (COPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to affect directly the thermal state of the subsystem.

- AUXILIARY THERMAL USED (CAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel supplied to the subsystem.

- AUXILIARY ELECTRICAL FUEL (CAE) is the amount of electrical energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (CSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

ENVIRONMENTAL SUMMARY

The environmental summary is a collection of the weather data which is generally instrumented at each site in the program. It is tabulated in this data report for two purposes--as a measure of the conditions prevalent during the operation of the system at the site, and as an historical record of weather data for the vicinity of the site.

- TOTAL INSOLATION (SE) is accumulated total solar energy incident upon the gross collector array measured at the site.

- AMBIENT TEMPERATURE (TA) is the average temperature of the environment at the site.

- WIND DIRECTION (WDIR) is the average direction of the prevailing wind.

- WIND SPEED (WIND) is the average wind speed measured at the site.

- DAYTIME AMBIENT TEMPERATURE (TDA) is the temperature during the period from three hours before solar noon to three hours after solar noon.

APPENDIX B

# SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS FOR THE REEDY CREEK UTILITIES

## I. INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each subsystem every 320 seconds. This data is then numerically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this evaluation.

Data samples from the system measurements are numerically integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This numerical integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of numerical integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu/ft$^2$-hr, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [M100 \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in $lb_m$/min and $\Delta H$ is the enthalpy change, in Btu/$lb_m$, of the fluid as it passes through the heat exchanging component.

For a liquid system $\Delta H$ is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}p$ is the average specific heat, in Btu/($lb_m$-°F), of the heat transfer fluid and $\Delta T$, in °F, is the temperature differential across the heat exchanging component.

For an air system $\Delta H$ is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/$lb_m$, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document, given in the list of references, was prepared by an inter-agency committee of the government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each numerical integration process, therefore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED IN MONTHLY PERFORMANCE REPORT

NOTE: - MEASUREMENT NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

SITE SUMMARY REPORT

INCIDENT SOLAR ENERGY (BTU)

$$SEA = (1/60) \times \Sigma\, [I001 \times AREA] \times \Delta\tau$$

INCIDENT SOLAR ENERGY PER UNIT AREA ($BTU/FT^2$)

$$SE = (1/60) \times \Sigma\, I001 \times \Delta\tau$$

COLLECTED SOLAR ENERGY (BTU)

$$SECA = \Sigma\, [M100 \times CP \times (T150 - T100)] \times \Delta\tau$$

COLLECTED SOLAR ENERGY PER UNIT AREA (BTU/SQ. FT.)

$$SEC = \Sigma\, [M100 \times CP \times (T150 - T100)/AREA] \times \Delta\tau$$

AVERAGE AMBIENT TEMPERATURE (DEGREES F)

$$TA = (1/60) \times \Sigma\, T001 \times \Delta\tau$$

TOTAL SYSTEM OPERATING ENERGY (BTU)

SYSOPE = ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

AVERAGE BUILDING TEMPERATURE (DEGREES F)

$$TB = (1/60) \times \Sigma\, [T600] \times \Delta\tau$$

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD/INCIDENT SOLAR ENERGY

ECSS OPERATING ENERGY (BTU)

$$CSOPE = 56.8833 \times \Sigma\, EP101 \times \Delta\tau$$

LOAD SUBSYSTEM SUMMARY:

HEATING ELECTRICAL SAVINGS (BTU)

HSVE = HEATING LOAD - HEATING OPERATING ENERGY

COOLING ELECTRICAL SAVINGS (BTU)

$$\text{CSVG} = \frac{\text{(COOLING LOAD - COOLING AUXILIARY THERMAL ENERGY)}}{\text{COP}} - \text{COOLING OPERATING ENERGY}$$

where COP is the coefficient of performance of the auxiliary cooling equipment

HOT WATER ELECTRICAL SAVINGS = HOT WATER LOAD

TOTAL ELECTRICAL SAVINGS (BTU)

TSVE = HEATING ELECTRICAL SAVINGS + COOLING ELECTRICAL SAVINGS + HOT WATER ELECTRICAL SAVINGS - ECSS OPERATING ENERGY

TOTAL ENERGY CONSUMED (BTU)

TECSM = AUXILIARY THERMAL ENERGY + OPERATING ENERGY + SOLAR ENERGY COLLECTED

LOAD SUBSYSTEM SUMMARY (BTU):

HEATING LOAD

$$HL = \Sigma\,[M401 \times CP \times (T402 - T452)] \times \Delta\tau$$

COOLING LOAD

$$CL = \Sigma\,[M504 \times CP \times (T554 - T504)] \times \Delta\tau$$

HOT WATER LOAD

$$HWL = \Sigma\,[M300 \times CP \times (T350 - T300)] \times \Delta\tau$$

SYSTEM LOAD (BTU)

SYSL = HL + CL + HWL

HEATING SOLAR FRACTION (PERCENT)

HSFR = 100 x (HEATING SOLAR ENERGY/HEATING LOAD)

COOLING SOLAR FRACTION (PERCENT)

CSFR = 100 x (1 - COOLING AUXILIARY THERMAL ENERGY/COOLING LOAD)

HOT WATER SOLAR FRACTION (PERCENT)

HWSFR = 100 x (HOT WATER SOLAR ENERGY/HOT WATER LOAD)

SOLAR ENERGY USED:

HEATING SOLAR ENERGY (BTU)

$HSE = \Sigma\ [M401 \times CP \times (T402 - T452)] \times \Delta\tau$

COOLING SOLAR ENERGY (BTU)

$CSE = \Sigma\ [M502 \times CP \times (T502 - T552)] \times \Delta\tau$

HOT WATER SOLAR ENERGY (BTU)

$HWSE = \Sigma\ [M300 \times CP \times (T350 - T300)] \times \Delta\tau$

TOTAL SOLAR ENERGY TO LOADS (BTU)

SEL = HWSE + HSE + CSE

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSTEM LOAD/[AUXILIARY FOSSIL FUEL + 3.33 x (AUXILIARY ELECTRIC FUEL + SYSTEM OPERATING ENERGY)]

OPERATIONAL INCIDENT ENERGY (BTU)

$SEOP = (1/60)\ \Sigma\ [I001 \times AREA] \times \Delta\tau$

WHENEVER COLLECTOR PUMP IS RUNNING

COLLECTOR ARRAY EFFICIENCY

CAREF = SECA/SEA

ENERGY TO STORAGE (BTU)

$STEI = \Sigma\ [M100 \times CP \times (T150 - T100)] \times \Delta\tau$

ENERGY FROM STORAGE (BTU)

STEO = HOT WATER SOLAR ENERGY + HEATING SOLAR ENERGY + COOLING SOLAR ENERGY

CHANGE IN STORED ENERGY (BTU)

STECH = STORAGE CAPACITY x [HEAT CONTENT PREVIOUS SCAN - HEAT CONTENT PRESENT SCAN] WHERE STORAGE CAPACITY IS THE ACTIVE VOLUME OF THE TANK

STORAGE AVERAGE TEMP (DEGREES F)

$TST = (1/60)\ \Sigma\ [(T201 + T202 + T203) / 3] \times \Delta\tau$

STORAGE EFFICIENCY (BOTH HOT AND COLD STORAGE)

STEFF = (CHANGE IN STORED ENERGY + ENERGY FROM STORAGE) / ENERGY TO STORAGE

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = SOLAR ENERGY TO LOAD / INCIDENT SOLAR ENERGY

DIFFUSE INSOLATION (BTU/SQ. FT.)

$$= (1/60)\ \Sigma\ [I002] \times \Delta\tau$$

DAYTIME AMBIENT TEMP (DEGREES F)

$$TDA = (1/360)\ \Sigma\ [T001] \times \Delta\tau$$

$\pm$ 3 HOURS FROM SOLAR NOON

OPERATING ENERGY (BTU):

HEATING OPERATING ENERGY

$$HOPE = (56.88)\ \Sigma\ (EP403) \times \Delta\tau$$

COOLING OPERATING ENERGY

$$COPE = (56.88)\ \Sigma\ (EP401 + EP501 + EP502 + EP503 + EP504) \times \Delta\tau$$

TOTAL OPERATING ENERGY

SYSOPE = ECSS OPERATING ENERGY + HEATING OPERATING ENERGY + COOLING OPERATING ENERGY

AUXILIARY THERMAL ENERGY (BTU)

CAT = COOLING AUXILIARY THERMAL ENERGY

COOLING AUXILIARY ELECTRIC FUEL

CAE = CAT/COP

where COP is the coefficient of performance of the auxiliary cooling equipment

TOTAL AUXILIARY THERMAL ENERGY

AXT = CAT

TOTAL AUXILIARY ELECTRIC FUEL (BTU)

AXE = COOLING AUXILIARY ELECTRIC FUEL

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

SITE: REEDY CREEK 18. LOCATION: BUENA VISTA FL

ANALYST: C. WALLACE FDRIVE NO.: 20.

COLLECTOR TILT: 0.0 (DEGREES) COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 28.50 (DEGREES) RUN DATE: 6/04/79

| MONTH | HOBAR | HBAR | KBAR | RBAR | SBAR | HDD | CDD | TBAR |
|---|---|---|---|---|---|---|---|---|
| JAN | 1931. | 999. | 0.51736 | 1.000 | 999. | 197 | 52 | 60. |
| FEB | 2331. | 1243. | 0.53309 | 1.000 | 1243. | 184 | 86 | 62. |
| MAR | 2801. | 1582. | 0.56471 | 1.000 | 1582. | 94 | 122 | 66. |
| APR | 3231. | 1899. | 0.58775 | 1.000 | 1899. | 13 | 202 | 71. |
| MAY | 3485. | 1991. | 0.57125 | 1.000 | 1991. | 0 | 353 | 76. |
| JUN | 3571. | 1832. | 0.51313 | 1.000 | 1832. | 0 | 456 | 80. |
| JUL | 3518. | 1803. | 0.51243 | 1.000 | 1803. | 0 | 508 | 81. |
| AUG | 3318. | 1674. | 0.50448 | 1.000 | 1674. | 0 | 521 | 82. |
| SEP | 2948. | 1497. | 0.50771 | 1.000 | 1497. | 0 | 453 | 80. |
| OCT | 2463. | 1305. | 0.53001 | 1.000 | 1305. | 0 | 288 | 74. |
| NOV | 2022. | 1095. | 0.54170 | 1.000 | 1095. | 75 | 123 | 67. |
| DEC | 1814. | 925. | 0.51004 | 1.000 | 925. | 170 | 62 | 62. |

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.